Stability of Armour Units in Oscillatory Flow

Burcharth, Hans F.; Thompson, A. C.

Published in:
Proceedings of Coastal Structures '83 : a specialty conference on the design, construction, maintenance, and performance of coastal structures

Publication date:
1983

Document Version
Publisher's PDF, also known as Version of record

STABILITY OF ARMOUR UNITS IN OSCILLATORY FLOW

Hans F. Burcharth *
A. C. Thompson **

ABSTRACT

Despite numerous breakwater model tests very little is known today about the various phenomena and parameters that determine the hydraulic stability characteristics of different types of armour. This is because separation of the parameters is extremely difficult in traditional tests. With the object of separating some of the factors a deterministic test, in which horizontal beds of armour units were exposed to oscillatory flow, was performed in a pulsating water tunnel. The threshold of movement was studied for two extremeties in the range units, namely Dolosse and rocks weighing from 14 g to 130 g. The test results revealed no significant differencies in hydraulic stability of Dolosse and rocks of the same weight. Moreover units of different sizes showed the same stability, and no viscous scale effect was observed. The paper discusses these results in relation to realistic breakwater situations. It is argued that the permeability of the armour in giving a "reservoir effect" is a determining factor for the stability characteristics of the armour. The test results are compared with other works on threshold of movements of sediments.

As it is not within the scope of this paper to discuss the mechanical strenght problem of armour units, only hydrodynamic aspects are dealt with.

INTRODUCTION

Many types of concrete units for armouring rubble breakwaters have been designed with the object of achieving a good stability to weight ratio and low production costs. As no systematic information exists on the stability of armour units the designer often finds it difficult to make a choice between the various types available to him. Even though quite a lot of breakwater model tests and deterministic investigations of flow in rubble mound structures have been performed, a satisfactory understanding of the physics behind the differences in behaviour of slender and bulky units has not been reached.

Generally for units of the same weight and density slender ones like Dolosse exhibit a better *hydraulic* stability than bulky ones like cubes. However, the different types of armour do not respond in the same way to changes in wave characteristics. Whillock and Price (1976) for example, have demonstrated that oblique wave attack can dislodge Dolosse more easily than waves approaching at right angles and Burcharth (1977) has shown that the stability of a Dolos slope decreases as the wave period increases. Both effects are in contrast to the behaviour of slopes made of rocks. It was thought that the explanation for this was that Dolosse are more vulnerable to flows parallel to the surface because of their high drag to weight ratios. This suggestion was supported by Brebner (1978), who tested Dolosse laid as

* Professor, University of Aalborg, Denmark.
** Senior lecturer, The Royal Military College of Science, Shrivenham, England.

a bed in steady flow and found them to be only as stable as stones of the same weight and density.

One of the objects of the studies described in this paper was to explain some of the differences in the hydraulic stability of slender and bulky units. Beds of Dolosse and stones, which represent two extremities in the variety of units, were subjected to oscillatory flows parallel to the cover layer for the study of their hydraulic stability, i.e. displacement and rocking of the units.

This type of test was chosen because the flow characteristics could be controlled very accurately and because the observations of the movements of the units were easy. Although the parallel flow test does not reproduce the flow in a breakwater situation there are similarities to flow over a wide extended berm and to run up and run down of long waves on a flat slope.

Another object was to examine some of the scale effects that might arise in rubble mound breakwater models of different sizes. This was possible because units of different sizes (14.5 - 130 g) were used in the tests.

EXPERIMENTAL METHOD

Horizontal beds of Dolosse and rocks were exposed to sinusoidally oscillatory flow in the pulsating water tunnel at Hydraulics Research Station, Wallingford, which has a working section of 0.50 m width and 1.9 m height. Periods from 3.3 to 12. sec. and corresponding semi-amplitudes from 0.50 to 2.90 m were employed. Three sizes of Dolosse and rocks were tested. The models consisted of a layer of small stones laid on the tunnel floor to obtain friction. Armour units corresponding to approximately three layers were then placed. This relatively thick armour layer was used to prevent the filterlayer from influencing the stability of the armour top layer. Dolosse were placed in one half of the model and crushed rocks of approximately the same mass in the other. The edges were restrained by chicken wire leaving a test section open in which the units could be moved freely by the flow. Details of the models are given in Fig. 1 and Table 1.

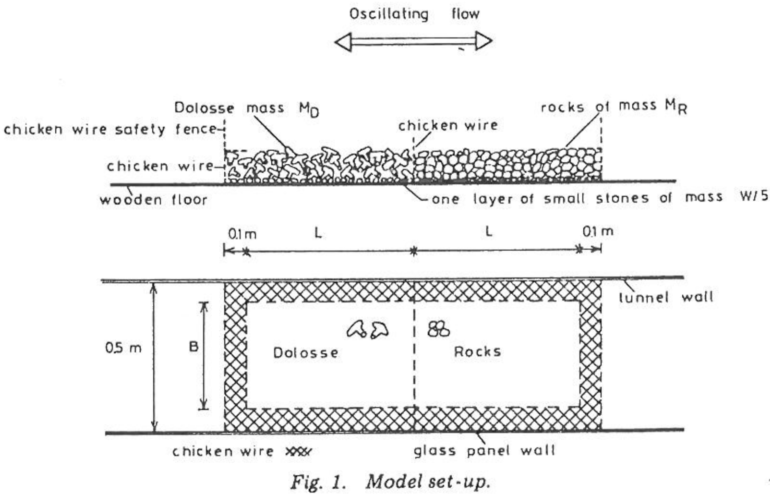

Fig. 1. Model set-up.

Table 1. Model characteristics.

Test no	2 and 3	1 and 4		5
Height of Dolos, H (cm)	3.45	5.34		7.0
Mass of Dolos, M_D (g)	14.5	65.0		130
Density of Dolos, ρ_{SD} (g cm^{-3})	2.32	2.36		2.40
Equivalent sphere diameter, $d_D = (6M/\pi\,\rho_{SD})^{1/3}$ (cm)	2.28	3.75		4.69
Number of Dolosse in test section, N_D	300	300		210
Packing number, $\varphi_D = N_D(M_D/\rho_{SD})^{2/3}$	1.05	1.10		1.07
Bulk porosity, $P_D = 1 - \varphi_D/(3C_D)$, $C_D \equiv 1$	0.65	0.63		0.64
Average mass of rocks, $\overline{M}_R$ (g)	15	55	65	124
Max/min mass of rocks, (g)	18/12	69/42	91/46	149/97
Density of rocks, ρ_{SR} (g cm^{-3})	2.66	2.66		3.0
Equivalent sphere diameter, $d_R = (6M/\pi\,\rho_{SR})^{1/3}$ (cm)	2.21	3.40	3.59	4.29
Shape of rocks fairly cuboidal, i.e. elongation ratio (intermediate length/greatest length) and flakiness ration (shortest length/intermediate length $\gtrsim 2/3$				
Length of test section, L (cm)	38	60		70
Width of test section, B (cm)	26	40		40

The packing densities of the armours are within the range used in prototype breakwaters. Although it is difficult to verify a certain number of layers of Dolosse in a pack the factor 3, corresponding to the three layers, is used for calculation of P_D.

The height of the boundary layer in the tunnel without the models was smaller than the height of the models for the applied range of periods and strokes. Velocity profiles were not measured during the tests.

The procedure for carrying out the tests was to set the period of the oscillating flow and increase the amplitude of the water motion gradually until some movement of the units was seen through the glass panels in the tunnel wall. It was usually possible to set the stroke so that just one unit was rocking. As the stroke was increased more units would rock, so that levels of excitation at which for example 3, 5, 8 and > 8 units rocked could be identified. In these states of motion the units would never be displaced from their initial position in the model and be removed to another position. If the amplitude was increased much past the 8 rocking level, R^8, then one of the more exposed units would be displaced to another position, often at the end of the model against the chicken wire "safety" fence. In most cases the amplitude could be set so that only one or two units would be displaced no matter how long testing was continued at this setting. This was true up to about 4 displacements D^4, so that amplitudes for D^1, D^2, D^4, $D^{>4}$ could be found, but at $D^{>4}$ the pack was steadily breaking up.

When counting units, only those at least one unit away from the edge were included and when displacements were reckoned only those units which had not been displaced before at that setting of the period were included. Once all the amplitudes giving R^1 to $D^{>4}$ at a particular period had been found the period was changed and the stroke increased from a small value to find the R^1 to $D^{>4}$ levels at this new period. The periods were generally taken in order 3.3, 4, 5, 6, 7, 8, 9 and 10 seconds followed by a check on at least one of the earlier periods. It was not usually possible to reach the $D^{>4}$ condition at periods of 3.3 and 4 seconds because of the safety limit on the tunnel stroke. The test at this $D^{>4}$ condition would usually be kept short so that the model did not need to be rebuilt before going on to another period. The various degree of rocking were quite easy to distinguish except perhaps at the very longest periods, when all the units would move at one instant separated by a large interval from the next movement.

The visual method of recording the movements of the units might appear to be subjective and therefore also unreliable. To check this problem several tests were run by the two authors independently. It was found that the two sets of results from each test were surprisingly close.

TEST RESULTS

Hydraulic stability

The simplest way of displaying the results is to plot the amplitude of the water motion, a, against the period, T, for the condition when units are just displaced, that is D^1 if available, or D^2-D^4 if not. This is done for the three sizes of Dolosse and stones in Figs. 2-4. It should be noted that for each of the three sizes of units there are differencies in weight and density for Dolosse and rocks, see Table 1. The weights are nearly the same if the mean weight of the rocks is considered, but the densities are different although characteristic in that the densities compare to those often found in prototype for the two types of units.

From Figs. 2-4 it is apparent that there is only a small difference in the stability of the Dolosse and the rocks. If the three figures are compared, or all the results plotted in one figure, Fig. 5, it appears that at any setting of the period T all sizes of Dolosse and stones are about to move at the same amplitude, although there is a tendency that the heavier units require a slightly bigger amplitude to move them at any given period.

Since the behaviour of the Dolosse and rocks is the same in that big units do not seem much more stable than small ones, the safest conclusion is probably that, if usual densities are considered, Dolosse and rocks of the same weight show nearly the same stability in this flow.

To understand this and to see if there are any scale effects, we need a dimensionless plot. A logical step from the plot of a versus T is a plot of $\hat{a}/d$ versus $T\,(g'/d)^{0.5}$ where $g' = g(\rho_S/\rho - 1)$ and ρ_S and ρ are densities of units and water respectively. The characteristic length of the units, d, is taken as the equivalent sphere diameter of equal volume, i.e. $d = (6M/\pi\rho_S)^{1/3}$ to make comparison with data of other researchers possible. This plot is shown in Fig. 6. It will be seen that for a large and small unit at the same values of a and T, the large one has smaller values of a/d and $T\,(g'/d)^{0.5}$ and could be unstable at the same time as the small unit.

This reduced stability at low values of a/d is due, either to an increased friction factor or to greater inertia forces, as shall be discussed later.

It is also seen that the stability of the Dolos models is better than that of the rock models, when volume and density of the units are taken in account, the Dolosse requiring a relative amplitude about 20 % greater to move them at any given reduced period.

Scale effects

Another important question, which Fig. 6 answers, is that of scale effects. If the models follow a Froude scaling law, i.e.

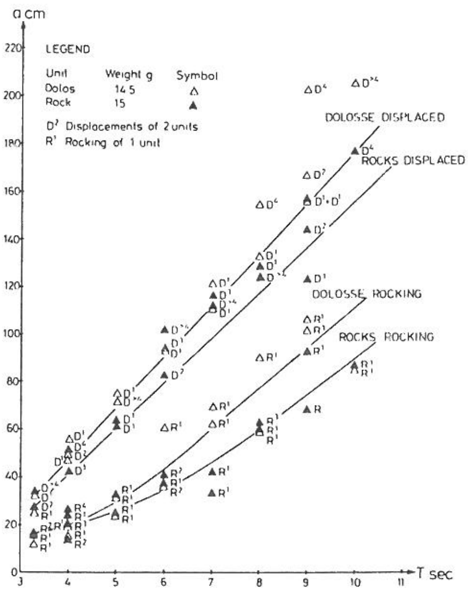

Fig. 2. Amplitude versus period at threshold, 14.5 g and 15.0 g units.

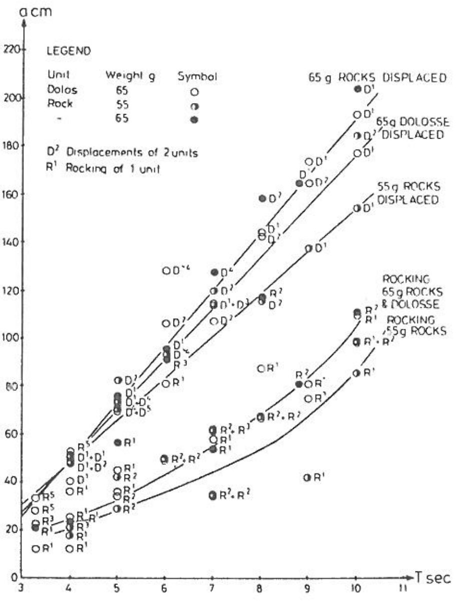

Fig. 3. Amplitude versus period at threshold, 55 g and 65 g units.

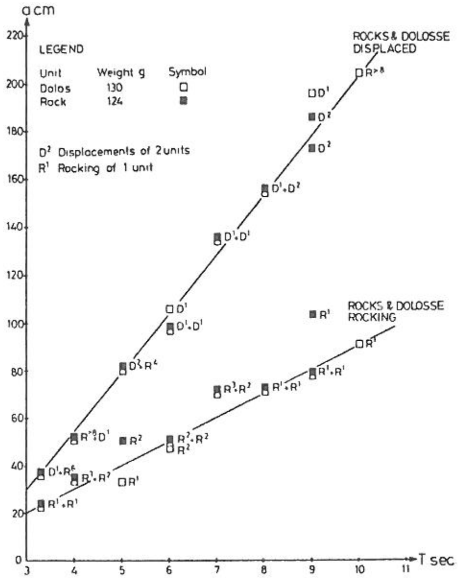

Fig. 4. Amplitude versus period at threshold, 124 g and 130 g units.

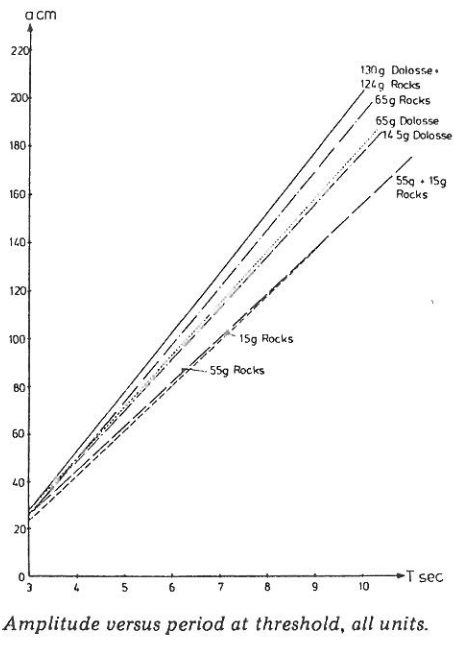

Fig. 5. Amplitude versus period at threshold, all units.

$$(a/T) / (g'd)^{0.5} = \text{constant},$$

any size of unit should give a point on the same line in the a/d versus T $(g'/d)^{0.5}$ diagram when it is about to move. This is so for the three sizes of stones for a/d below about 40. Above this value some of the results for the smaller stones appear more stable. For the Dolosse the 2 larger sizes lie on the same line, but the smallest size is a little more stable at all values of a/d. This is the opposite effect to what one would expect if viscous forces were important and it may well be due to a slightly stronger construction of the small model. This can easily happen because any hand compaction of constant force will make the smaller models relatively stronger. If the results from each model are looked at separately it is seen that the plots fit very well to straight lines, which means that the models obey the Froudian model law in the tested range of flow. This does not necessarily mean that there are no viscous forces of some size present as a fairly constant ratio of viscous forces to inertia forces could be present in all tests.

COMPARISON WITH SEDIMENT THRESHOLD THEORY AND OTHER THRESHOLD DATA

The problem of sediment threshold in oscillatory flow has been investigated by several writers and it is possible to compare our results with theirs. The nearest in size was the coarse sediment tested by Rance and Warren (1968). They produced data plot of $a/(g'T^2)$ against a/d. In Fig. 7 our data are plotted in the same way and compared with the range of Rance and Warren's results. It is seen that the data points are just outside this range, but the trends in all the test series are the same. Total agreement between results cannot be expected because of differences in the models. The main difference is that in our experiments there is an edge effect which stems from the finite height over the tunnel floor of the edge of our models. The significance of the choice of variables in Fig. 7 is not immediately clear since $a/(g'T^2)$ represents the ratio of inertia (added mass type force) to gravity force on a bed particle and a/d the ratio of drag to inertia force (like the Keulegan Carpenter number).

A fuller explanation might emerge from a comparison with Sleath's work (1978). The starting point is the Shield's parameter for oscillatory flow, see Komar et al. (1974) and Madsen et al. (1975), which reads

$$\theta = \frac{\tau_{max}}{\rho g' d} = \frac{f_w \frac{1}{2} \rho (a\omega)^2}{\rho g' d} = \frac{f_w U_o^2}{2g'd} , \tag{1}$$

where ω is the angular frequency of oscillation, $U = a\omega$ and f_w is Jonsson's wave friction factor (1965), which according to Swart's (1974) can be written as $f_w = \exp(5.21\ (k/a)^{0.19} - 5.98)$ valid for rough turbulent flow in the range $a/k > 1.7$. k is the Nikuradse roughness parameter.

Sleath discusses the general validity of eq. (1) and proposes a modified Shield's parameter

$$\psi_C = \frac{f_1 U_o^2}{2 g' d} , \tag{2}$$

where ψ_C may be thought of as the ratio of the maximum resultant of all destabilizing fluid forces to the immersed weight. The indices C refers to the threshold of movement. f_1 is the ratio of this fluid force to $1/2\ \rho\ U_o^2$ times the exposed area. ψ_C is a measure of the strength of the bed. Eq. (2) enables Sleath to get the results of various authors on one single curve

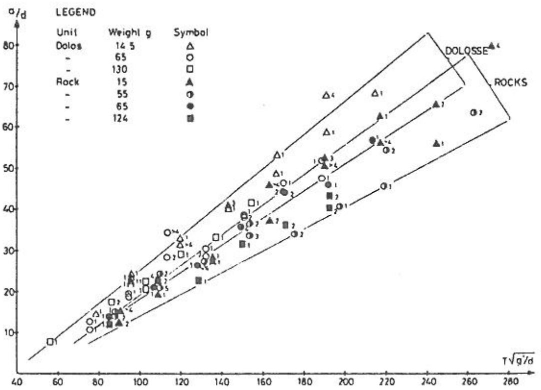

Fig. 6. *Relative amplitude versus reduced period at threshold.*

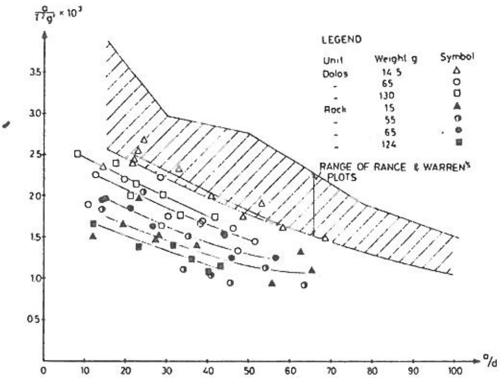

Fig. 7. *Acceleration number versus relative amplitude at threshold D^1 and D^2.*

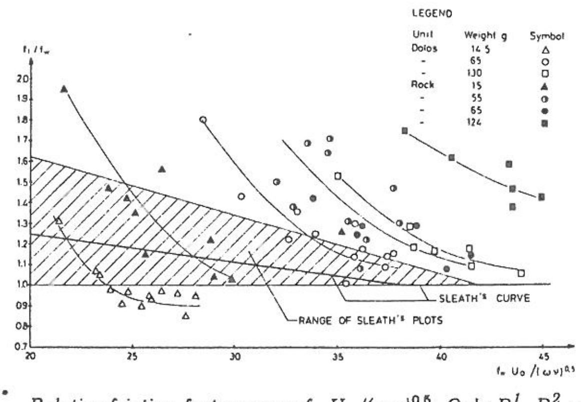

Fig. 8. *Relative friction factor versus $f_w\, U_o/(\omega\, \nu)^{0.5}$. Only D^1, D^2 and D^3.*

f_1/f_w versus $f_w U_o/(\nu\omega)^{0.5}$ by adjusting ψ and f_1. ν is the kinematic viscosity. f_w was found by taking the equivalent sphere diameter d as the Nikuradse roughness. The parameter ψ_C was found by Sleath to have the value 0.044 when the non-dimensional grain size

$$d_* \equiv (g'/\nu^2)^{1/3} d > 200$$

The size of units used in our tests corresponds to $d_* \geqslant 488$. Thus we take $\psi_C = 0.044$ and produce in Fig. 8 the same sort of relative friction factor plot as Sleath. For the calculation of f_w the Nikuradse roughness is set equal to the equivalent sphere diameter, d in the case of rocks and equal to 0.83 d in the case of Dolosse. These roughness values were determined in steady flow over bed of rocks (15 g average) and Dolosse (14.5 g).

From Fig. 8 it is seen that our results for the small rocks (15 g) fall quite close to the mean line obtained by Sleath. The results for the small Dolosse are displaced from the others as they reach values of f_1/f_w below one. The parameter $f_w U_o/(\omega\nu)^{0.5}$ could be written as $f_w (U_o a/\nu)^{0.5}$ or $f_w R_E^{0.5}$, where R_E is the amplitude Reynolds number defined by Jonsson. The parameter therefore gives a measure of the importance of viscous forces.

Our results do not seem to show the same overall variation with $f_w R_E^{0.5}$ (i.e. general influence of viscous forces) which occurs in Sleath's plot, since separate graphs can be drawn for each size of unit. (It should be noted that the upper end of Sleath's mean line is based only on three or four test results in the range $35 < f_w R_E^{0.5} < 42$).

In Fig. 9 f_1/f_w is plotted against a/d. It is seen that basically the same variation is apparent for all sizes of unit, but the results for the smaller Dolosse appear to be displaced from the others, as would occur if they required a higher value of ψ_C, i.e. the small Dolosse model was stronger. Fig. 8 and Fig. 9 therefore seem to tell the same story as our original plot, Fig. 6, that scaling effects are small but the smallest Dolosse model may have been stronger than the other models. It is seen that a noticeable inertia effect is present at a/d as high as 10.

By adjusting ψ_C for the various test series, an approximately vertical shift of the points in Fig. 9 leading to a relatively good fit to one curve with $f_1/f_w = 1$ as asymptote, can be obtained.

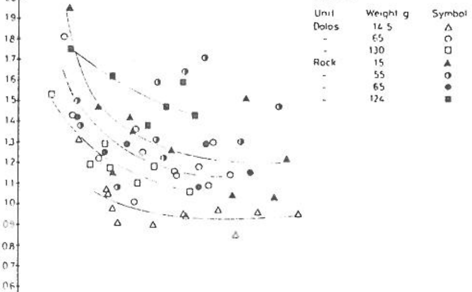

Fig. 9. Relative friction factor versus relative amplitude. D^1, D^2 and D^3.

The experimental results in Fig. 6 can be predicted by the threshold theory of Sleath. From eq (2) we find by inserting $U_o = 2\pi a/T$

$$T(g'/d)^{0.5} = \pi(2f_1/\psi_C)^{0.5} a/d$$

Taking $f_1 = f_w$ and $\psi_C = 0.044$ gives lines (one for Dolosse, one for rock) within the total range of the experimental results in Fig. 6. By taking $\psi_C = 0.034$ a better agreement is obtained.

The onset of rocking can be analysed in a similar way, and it is found that the threshold of rocking corresponds approximately to a value of $\psi_C = 0.017$.

INTERPRETATION OF THE TEST RESULTS IN RELATION TO RUBBLE MOUND ARMOUR LAYERS

The oscillatory flow over a horizontal bed might be compared to wave induced flows over a wide submerged berm and across a sloping breakwater round head. Also some parts of the run up and run down of long waves on a flat slope create similar flows. Due to limitations of the pulsating water tunnel it was not possible to simulate the small a/d ratios (< 5), which are characteristic in the mentioned breakwater flows. This gives limitations in the evaluation with respect to breakwaters.

The reservoir effect in sloping armour layers

In the test the voids between the units are permanently filled with water unlike the run-up and run-down zone of a breakwater where the voids are filled with air during wave recession. The air filled voids give a "reservoir effect" that reduces not only the run-up and run-down, but also the overflow velocities. A large porosity of the armour gives a strong reservoir effect. This effect is believed to be the reason for the high hydraulic stability of Dolosse slopes exposed to steep, short waves (shallow water situations).

The reservoir effect is reduced in the case of long waves, because such waves carry more water per wave onto the slope and consequently only a relatively smaller part can be stored in the voids. The result is higher overflow velocities and reduced hydraulic stability of the armour. The reduction in stability by long wave attack is therefore more pronounced for armour with high permeability. This might explain why a permeable armour, which relies on a pronounced reservoir effect, is more vulnerable to long wave attack than armour of bulky units.

The results presented in this paper do not prove this reservoir theory, but they support it by showing reduced stability of the very porous armour when submerged. The stabilizing prestressing effect, which is present in a sloping armour, is not present in a horizontal bed. This effect, which is discussed by Price (1979) is significant in porous armour of interlocking units, but only until a high degree of damage, i.e. a stage of displacements by liquifaction, is reached. However, it is believed that in the case of short waves high permeability more than prestressing-interlocking is the reason for the good hydraulic stability of Dolosse armour.

Dissipation of energy

Besides giving a reservoir effect a high permeability of the armour is useful also because more energy is dissipated in the flow through the voids. It follows from basic hydrodynamics that the bigger the voids, i.e. the bigger the cross sections of the flow channels, the more energy is dissipated, other things being equal. Therefore the large voids in rough porous armour like Dolosse are beneficial. However, this effect is relatively greater in short waves than in long waves, where a lot of energy is bound in the overflow.

Submerged berms and round heads

The test results and the above hypothesis suggest that for a wide submerged berm and for the parts of round heads where the slopes are small in the direction of the wave propagation a slender interlocking type of unit will not be significantly more stable than a bulky type of the same density. Moreover, for constant density, increased stability is not obtained unless the size (weight) of the unit is increased significantly. It follows from this that the best way of gaining a better hydraulic stability in these situations is to increase the unit density.

Relation between initiation of rocking and displacement

In real breakwaters the movement of units is very important because of the limited mechanical strength of concrete units. These might be damaged before the conventional stability limit of displacement is reached, Burcharth (1981). In the tests both Dolosse and rocks started to rock at about half the amplitude needed to produce displacement at any period. This observation might hold for other types of unit.

Shape of units

It emerged from the tests that big Dolosse and rocks are not much more stable than small units. This is because the friction factor increases rapidly as the ratio of amplitude to roughness decreases, and for Dolosse and rocks the roughness is approximately equal to the equivalent sphere diameter. Although the test flow is somewhat special in relation to the breakwater situations, the results do suggest that there might be advantages to a unit which increased in weight but not in roughness, e.g. permeable cubes laid in brick-wall fashion. This observation relates to the hydraulic aspects only and not to construction problems.

Model scale effects

The sizes of units in the tests cover the range normally encountered in modelling (the few existing giant flumes not included), but we cannot, of course, produce results approaching prototype scale. Moreover scale effects due to air entrainment, breaker types, filterlayers, and corematerial etc. are not dealt with. Only the viscous effect in submerged cover layers was studied.

Although drag forces are dominant in the tested range of flow no viscous scale effect was found. It might then be concluded that in wave generated oscillatory flows related to submerged armour, where the ratios of inertia to drag forces are bigger, there will be no viscous scale effect in even small scale models.

ACKNOWLEDGEMENTS

The model tests described in this paper were carried out at the Hydraulics Research Station, Wallingford in 1979 and 1980. The authors express their thanks to the Director and his staff for their kind assistance.

REFERENCES

Brebner, A. — Performance of Dolosse Blocks. In an Open Channel Situation. Proc. 16th Conference on Coastal Engineering, Hamburg, 1978.

Burcharth, H. F. — The Effect of Wave Grouping on On-Shore Structures. Coastal Engineering, 2, 1979.

Burcharth, H. F. — Full-Scale Dynamic Testing of Dolosse to Destruction. Coastal Engineering, 4, 1981.

Burcharth, H. F. — A Design Method for Impact Loaded Slender Armour Units. Bulletin no 18. Laboratoriet for Hydraulik og Havnebygning, University of Aalborg, DK-9000, Denmark, 1981.

Jonsson, I. G. — Friction Factor Diagrams for Oscillatory Boundary Layers. Progress Report no 10, Technical University of Denmark, Copenhagen, 1965.

Komar, P. D. and Miller, M. C. — Sediment Threshold under Oscillatory Waves. Proceedings. 14th Conference on Coastal Engineering, Copenhagen 1974.

Madsen, O. S. and Grant, W. D. — The Threshold of Sediment Movement under Oscillatory Water Waves, a Discussion. Journal of Sedimentary Petrology, Vol. 45, no 1, 1975.

Price, W. A. — Static Stability of Rubble Mound Breakwaters. Dock & Harbour Authority. Vol. LX no 702, 1979.

Rance, P. J. and Warren, N. F. — The Threshold of Movement of Coarse Material in Oscillatory Flow. Proceedings. 11th Conference on Coastal Engineering, London, 1968.

Sleath, J. F. A. — Measurements of Bed Load in Oscillatory Flow. ASCE Journal, WW4, Vol. 104, 1978.

Swart, D. H. — Offshore Sediment Transport and Equilibrium Beach Profiles. Delft University Technology Diss., Delft Hydr. Lab. Publ. 131, 1974.

Whillock, A. F. and Price, W. A. — Armour Blocks as Slope Protection. Proc. 15th Conference on Coastal Engineering, Honolulu, 1976.